THE DUCK REDUX: AN IMPROVED PROPER MOTION UPPER LIMIT FOR THE PULSAR B1757–24 NEAR THE SUPERNOVA REMNANT G5.4–1.2

J. A. BLAZEK,[1] B. M. GAENSLER,[1,2,3] S. CHATTERJEE,[4,1] E. VAN DER SWALUW,[5] F. CAMILO[6] AND B. W. STAPPERS[7,8]

ABSTRACT

"The Duck" is a complicated non-thermal radio system, consisting of the energetic radio pulsar B1757–24, its surrounding pulsar wind nebula G5.27–0.90 and the adjacent supernova remnant (SNR) G5.4–1.2. PSR B1757–24 was originally claimed to be a young ($\approx 15\,000$ yr) and extreme velocity ($\gtrsim 1500$ km s^{-1}) pulsar which had penetrated and emerged from the shell of the associated SNR G5.4–1.2, but recent upper limits on the pulsar's motion have raised serious difficulties with this interpretation. We here present 8.5 GHz interferometric observations of the nebula G5.27–0.90 over a 12-year baseline, doubling the time-span of previous measurements. These data correspondingly allow us to halve the previous upper limit on the nebula's westward motion to 14 milliarcseconds yr^{-1} (5-σ), allowing a substantive reevaluation of this puzzling object. We rule out the possibility that the pulsar and SNR were formed from a common supernova explosion $\approx 15\,000$ yrs ago as implied by the pulsar's characteristic age, but conclude that an old ($\gtrsim 70\,000$ yr) pulsar / SNR association, or a situation in which the pulsar and SNR are physically unrelated, are both still viable explanations.

Subject headings: ISM: individual (G5.4–1.2) — pulsars: individual (B1757–24) — radio continuum: ISM — stars: neutron — supernova remnants

1. INTRODUCTION

The formation and subsequent evolution of pulsars are not yet fully understood. A powerful constraint on these processes is provided by an independent age estimate. In cases where both a pulsar and its associated supernova remnant (SNR) can be identified, an age estimate which is independent of both distance and inclination effects is simply $t_p = \Theta/\mu$, where Θ is the angular separation between the pulsar and its inferred birth site, and μ is the pulsar's proper motion (Migliazzo et al. 2002; Kramer et al. 2003). This can then be compared to the age of the system as expected from spin-down (e.g., Lorimer & Kramer 2005):

$$t_p = \frac{P}{(n-1)\dot{P}} \left[1 - \left(\frac{P_0}{P} \right)^{n-1} \right], \qquad (1)$$

where P is the current spin period, $\dot{P}$ is the time-derivative of P, P_0 is the period at birth, and n is the "braking index" (see further discussion in §3.2). Comparison of these two independent age estimates provides information on P_0 and n, i.e., on the processes which impart and then dissipate the considerable angular momentum of neutron stars (e.g., Gaensler & Frail 2000, hereafter GF00; Kaspi et al. 2001b). If one assumes that $P_0 \ll P$ and $n = 3$, Equation (1) reduces to the expression for the "characteristic age" of a pulsar, $\tau_c \equiv P/2\dot{P}$.

PSR B1757–24 is an isolated 125-ms pulsar, surrounded by the cometary radio and X-ray pulsar wind nebula (PWN) G5.27–0.90, which in turn is located just outside the SNR G5.4–1.2 (Caswell et al. 1987; Manchester et al. 1991; Frail & Kulkarni 1991; Frail et al. 1994b; Kaspi et al. 2001a). As shown in Figure 1, the combined system has a distinctive morphology which has led to it being termed "the Duck". Because of the proximity of the pulsar to the SNR, and because the PWN morphology suggests that the pulsar is moving away from the SNR interior, it has been widely assumed that the pulsar and the SNR are physically associated. The SNR and PWN also have very similar H I absorption spectra, both suggesting a distance of ~ 5 kpc (Frail et al. 1994b), and consistent with the distance of 5.1 kpc implied by the pulsar's dispersion measure and the Galactic electron density model of Cordes & Lazio (2002). We consequently adopt a common distance of 5 kpc for pulsar, PWN and SNR in further discussion.

PSR B1757–24 has a characteristic age $\tau_c = 15$ kyr (Manchester et al. 2005). If we assume $t_p = \tau_c$ and that the pulsar has traveled $\Theta = 16\farcs1 - 20\farcs6$ from the SNR's center in its lifetime (Frail et al. 1994b),[9] this implies a westward proper motion for the pulsar of magnitude $\mu = \Theta/\tau_c = 63 - 80$ mas yr^{-1}. However, radio interferometric observations of the western tip of the PWN taken at the Very Large Array (VLA) over 6.7 years yielded a surprising 5-σ upper limit $\mu < 25$ mas yr^{-1} (GF00), implying a pulsar age $t_p > 39 - 50$ kyr $\gg \tau_c$, if the pulsar was born near the SNR's geometric center. GF00 used the stand-off distance of the PWN, the radius of the SNR and the separation of the pulsar from the SNR's center to derive a solution for the system's evolution which predicted $t_p \sim 90 - 170$ kyr and $\mu \sim 10$ mas yr^{-1}. Subsequently, Thorsett et al. (2002, hereafter TBG02) observed

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; blazek@post.harvard.edu

[2] Alfred P. Sloan Research Fellow

[3] Present address: School of Physics A29, The University of Sydney, NSW 2006, Australia; bgaensler@usyd.edu.au

[4] Jansky Fellow, National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903

[5] Royal Netherlands Meteorological Institute (KNMI), PO Box 201, 3730 AE De Bilt, The Netherlands

[6] Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027

[7] Stichting ASTRON, Postbus 2, 7990 AA Dwingeloo, The Netherlands

[8] Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

[9] The range of values quoted for Θ reflects the uncertainty in locating the pulsar's presumed birthplace. This results from the fact that the pulsar's inferred trajectory does not pass through the SNR's geometric center (Fig. 1; Frail et al. 1994b). See §3.2 for further discussion.

the pulsar itself with the VLA over a 3.9-year baseline, and placed an independent upper limit on westward proper motion[10] of $\mu < 37$ mas yr^{-1}. TBG02 argue that this is most easily explained if PSR B1757–24 and SNR G5.4–1.2 are unrelated, and if the pulsar is instead moving away from the center of the PWN G5.27–0.90. Assuming $t_p \approx \tau_c$, one can then predict a proper motion $\mu \sim 5$ mas yr^{-1}. As a further alternative, Gvaramadze (2004) has argued that this system results from a massive high-velocity progenitor star which went supernova inside its wind-blown bubble. The pulsar began its life substantially offset from the cavity's center, but the resulting SNR expands to take on the shape of the cavity. Gvaramadze (2004) subsequently develops a model in which $t_p \approx 54$ kyr, $\Theta \approx 6'$ and $\mu \approx 7$ mas yr^{-1}.

As an attempt to resolve this puzzling situation, we have conducted a new observation of the western cometary tip of PWN G5.27–0.90 (see inset to Fig. 1), which doubles the time baseline considered by GF00 to 12 years. In §2 we present our new observations and corresponding measurement of proper motion, while in §3 we we interpret these new results in the context of various possibilities proposed for the origin and evolution of this system.

2. OBSERVATIONS AND ANALYSIS

We have utilized three separate observations of G5.27–0.90, all carried out near 8.5 GHz with the VLA in its hybrid BnA configuration. The first two epochs were on 1993 Feb 02 and 1999 Oct 23, as discussed by GF00; the third epoch was on 2005 Jan 22, with an on-source integration time of 2.9 hr, and parameters otherwise the same as for the 1999 epoch reported by GF00. In particular, observations of G5.27–0.90 at all three epochs were phase-referenced to the source PMN J1751–2524, located $2\overset{\circ}{.}1$ from G5.27–0.90 (and for consistency using the same position for PMN J1751–2524 at each epoch, even though the best estimate of the position of this source has been updated by a small amount in recent years).

Analysis was carried out in the MIRIAD package (Sault & Killeen 2004). Data from the three epochs were reduced in almost identical fashion, making allowances for the slightly different correlator mode used in the 1993 data. The data were edited, calibrated, and imaged using square pixels of size 50 mas × 50 mas. The fields were then deconvolved using CLEAN and smoothed to a common resolution of $0\overset{''}{.}85$. The resulting images, shown in Figure 2, suggest that there have been slight structural changes between epochs.

The vertical dashed lines in Figure 2 demonstrate that motion at the 5-σ limit of GF00 could now have been easily discerned, and that any change in the position of the leading edge of the PWN is well below this level. We have quantified this result by measuring the shift between epochs using the MIRIAD task IMDIFF. IMDIFF finds the shift that minimizes the RMS of intensity fluctuations in the resulting difference map, employing cubic convolution interpolation to calculate shifts of a non-integer pixel number (Powell 1964).

Using the approach described by GF00, the shift that we determine between the 1993 and 2005 epochs is 71 ± 24 mas in a westward direction. However, this does not take into account any systematic errors present in this shift determination, nor does it use the combination of all three epochs. We have

thus determined the motion of the PWN by measuring the shift between all three possible pairs of epochs using IMDIFF. To characterize the statistical error in the reported shifts, for each pair a series of phase shifts were applied to the $u-v$ visibility of one epoch, resulting in images which had been shifted east or west by 0, 0.4, 0.8, 1.2, …, 4.0 pixels. This allowed us to probe the systematic errors introduced by IMDIFF for non-integer pixel shifts of a faint extended source in the presence of noise. To minimize the effects of any internal structural change in the PWN between epochs, the brightness distribution above a surface brightness of 70 mJy beam^{-1} was pegged at 70 mJy beam^{-1}, giving the nebula a largely uniform intensity out to its periphery. For each pair of epochs and each phase shift, IMDIFF was then run using 16 different sets of inputs, produced by alternating between four different spatial windows, by switching between the choice of epoch used as the reference image, and constraining IMDIFF to find a shift only in R.A., or in both R.A. and Decl. The ensemble of outputs from the combinations of these options allowed us to characterize, for each input trial shift, a mean fitted shift in the R.A. direction and its systematic error. The recovered shifts were then plotted against the input shifts and fit with a weighted linear least-squares model. The ordinate intercept then represented the best-fit measured motion between each pair of epochs. The statistical error on this estimate was determined by calculating the standard error in the mean amongst the residuals between input and mean output values for the 21 trial shifts for each pair. The statistical and mean systematic errors were then combined in quadrature to give the final error estimate for each pair. Other sources of error, such as phase transferral and calibration error, are negligible compared to these effects and have not been incorporated in this analysis.

We then examined the correlation between shifts between each of the three epoch pairs and the time separation between these pairs. If steady westward motion was detected, we would have expected these two quantities to correlate, but the data show no such trend. We conclude that despite our best efforts to minimize the effects of structural changes in the nebula between epochs, the underlying proper motion is too small in magnitude to be seen in the presence of the systematic errors introduced by these changes. We have correspondingly determined an upper limit on the source's motion by calculating the χ^2 of the best linear fit to the data, and then finding the larger of the two slopes for which χ^2 increases by 5-σ over this best-fit value.

Through this approach, we find an upper limit on westward proper motion of G5.27–0.90 of $\mu < 13.9$ mas yr^{-1}. This and previous estimates are shown in Table 1: it can be seen that this new result is nearly a factor of two more constraining than existing measurements. For $\Theta = 16\overset{'}{.}1 - 20\overset{'}{.}6$ as assumed above, the 5-σ lower limit on the system's age is $t_p = \Theta/\mu > 69 - 88$ kyr (see Table 1).

Note that because the X-ray and radio morphologies of G5.27–0.90 suggest proper motion purely in a westward direction, we have not included any shift in Decl. in our final proper motion estimates. In any case, the derived shift between each pair of epochs is consistent with zero proper motion in Decl.

Assuming a distance to the system of 5 kpc, we can infer an upper limit on the projected westward velocity for PSR B1757–24 of 340 km s^{-1}. This limit is consistent with the observed range of motions for other pulsars associated with SNRs (see Table 6 of Hobbs et al. 2005), and also with the overall projected velocity distribution of the young pulsar

population (Arzoumanian et al. 2002; Hobbs et al. 2005).

3. DISCUSSION

Since we have used the motion of PWN G5.27–0.90 as a proxy for that of PSR B1757–24, the two objects must move together rigidly for our limit to be applicable to the pulsar. As discussed by GF00, the pulsar could be moving faster than our upper limit if the stand-off distance between the pulsar and the head of the bow shock were steadily decreasing with time, as might be produced by the system encountering a sudden increase in density. However, this is unlikely to be the case since, if anything, the data in Figure 2 suggest that emission from the leading edge of the bow shock has slightly faded in brightness as a function of time. If this is naïvely interpreted as corresponding to a reduction in ambient density, then the stand-off distance could even be increasing with time, further strengthening our upper limit on the pulsar's motion. In any case the direct observations of the pulsar reported by TBG02 rule out a large disparity between the proper motions of the pulsar and its PWN.

The angular proximity and consistent distance estimates for PSR B1757–24 and SNR G5.4–1.2 obviously demand that the possibility of a physical association be considered. Further evidence strengthening the case for a genuine association are the high spin-down luminosity of the pulsar, the fact that the PWN's cometary tail points back toward the SNR's interior (seen in Figs. 1 and 2), and the edge-brightening and flatter spectral index of SNR G5.4–1.2 along its western rim near the pulsar (Fig. 1; Frail et al. 1994b). In the absence of any constraints on the PWN's proper motion or the pulsar's age, the simplest interpretation would seem to be that the pulsar was born reasonably close to the SNR's geometric center, has then moved outward, overtaken the SNR, and in the process has re-energized the shell's emission with its relativistic outflow of particles and magnetic fields (Shull et al. 1989). However, in §2 we have derived $t_p > 69 - 88$ kyr if the pulsar was born near the SNR's center. Since $\tau_c = 15$ kyr $\ll t_p$, the picture proposed above is problematic.

In the following discussion, we consider three possible solutions[11] to this difficulty: (1) the pulsar and the SNR are physically associated with an age $t_p \approx \tau_c$, but the pulsar was born substantially offset from the SNR's geometric center; (2) the pulsar and SNR are physically associated, but $t_p \gg \tau_c$; or (3) the two objects have no physical association. We conclude by considering the nature of G5.27–0.90, which we argue provides additional clues to distinguish between these possibilities.

3.1. Association Involving a Young Pulsar

In the case of a physical association, but with a supernova explosion substantially offset from the geometric center of the SNR, our upper limit on t_p can potentially be made consistent with the characteristic age. If the blast center of the SNR were considerably closer to the current location of the pulsar than the separation of $\Theta = 16'.1 - 20'.6$ assumed earlier, the predicted pulsar motion would be lower, and possibly could brought below the upper limit in Table 1.

A reasonable mechanism through which this large offset could have occurred is if the supernova occurred in the stellar

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[11] We acknowledge the existence of a variety of other explanations that have been proposed for PSR B1757–24 and SNR G5.4–1.2, such as have been discussed by Kundt (1992), Istomin (1994), Marsden et al. (2001) and Shi & Xu (2003). However, here we focus on three simple possibilities which can potentially be compared using available data.

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wind bubble of a moving progenitor star (Gvaramadze 2002). Expansion of a SNR into such a bubble could produce a remnant whose blast site is substantially separated from the geometric center (Gvaramadze 2004). In such a case, the pulsar could have been born inside the SNR but quite close to its present location, and the predicted proper motion would then be very low.

This explanation was viable for the upper limits obtained by GF00 and TBG02. However, for our new, more constraining proper motion measurement, the pulsar would need to have been born on the rim of or even outside the SNR to satisfy the requirement that $t_p \approx \tau_c$. While it is possible that the progenitor star was in the process of escaping its own wind bubble when the supernova occurred, such a system would produce an SNR significantly elongated and distorted along the east-west axis corresponding to the pulsar's motion (Różyczka et al. 1993; Brighenti & D'Ercole 1994), not consistent with the SNR morphology seen here.

Furthermore, since the pulsar was kicked randomly away from its birthplace, a wide separation between the neutron star birth site and the SNR's geometric center implies that there should most likely be a significant misalignment between the pulsar's direction of motion (as inferred from the PWN's morphology) and the vector joining the SNR's center to the pulsar's current position (Gvaramadze 2002; Migliazzo et al. 2002). Specifically, for an explosion occurring near the edge of the cavity, there is a $\approx 90\%$ probability that the misalignment between the projections of these two vectors will be larger than the $\approx 20°$ observed. The mild misalignment between the projections of these two vectors therefore makes a scenario in which the explosion was substantially off-center relatively unlikely.

3.2. Association Involving an Old Pulsar

As suggested by GF00 and Gvaramadze (2004), the case for a pulsar / SNR association can be made if the characteristic age is a significant underestimate of the system's true age. The solution proposed by GF00 predicts an evolved system consisting of an old SNR and a slow-moving pulsar, for which $t_p = 93 - 170$ kyr and $\mu = 7 - 10$ mas yr^{-1}, consistent with the upper limits found here. However, we then need to explain why $t_p \gg \tau_c$.

To consider this possibility, we must reconsider the assumptions underlying Equation (1). The braking index, n, is defined by the equation $\dot{\nu} = -K\nu^n$, where $\nu \equiv 1/P$. For spin-down via a magnetic dipole in vacuo, we expect $n = 3$. Following Blandford & Romani (1988), we separately define the "deceleration parameter", $\tilde{n} \equiv \nu\ddot{\nu}/\dot{\nu}^2$. If K and n are both constant, then $\tilde{n} = n$.

There are two situations in which the characteristic age, $\tau_c = P/2\dot{P}$, can underestimate the true age as required here. The first possibility is that $P \gg P_0$ and K is constant, but $n = \tilde{n} < 3$. For PSR B1757–24, Equation (1) can only yield $t_p > 69$ kyr for $P_0 < 13$ ms, and even then only for $\tilde{n} \approx 1$. In contrast, measurements of initial spin in most other systems suggest $P_0 \gtrsim 20$ ms (Migliazzo et al. 2002; Kramer et al. 2003), while in the few cases where $\tilde{n}$ has been determined, it is found that $1.4 < \tilde{n} < 2.9$ (Livingstone et al. 2005, 2006, and references therein). It thus seems unlikely that a viable set of parameters can describe the system via Equation (1).

The alternative is that K is not constant. In this case, Equation (1) no longer holds, and $\tilde{n} \neq n$ (see Blandford & Romani 1988). Either a changing magnetic field or a changing moment of inertia can cause K to vary with time (see e.g., Camilo

1996). In this case, the pulsar spin-down is uncoupled from the star's age, and rather traces the time scale on which K evolves.

While it seems unlikely that the star's moment of inertia could evolve substantially on this time-scale, the growth of the surface magnetic field is a possibility, as may result from thermoelectric instabilities in the crust or diffusion of magnetic flux from the star's interior (Blandford et al. 1983; Ruderman et al. 1998; Konenkov & Geppert 2001; Lin & Zhang 2004). If we assume $n = 3$ but $\tilde{n} < 3$, then τ_c underestimates the true age, and the surface magnetic field, B, grows with time (Lyne 2004). Indeed $\tilde{n} < 3$ is observed for all six pulsars in which this quantity has been accurately determined, while $dB/dt > 0$ is suggested in long-term timing signatures of several other pulsars (Lyne et al. 1996; Smith 1999; Lyne 2004). While $\tilde{n}$ has not been directly measured for PSR B1757–24, we can write as an order of magnitude estimate that the time scale for field growth has been $B/\dot{B} \sim \tau_c \approx 15$ kyr.

We further note that this does not require us to invoke a unique effect to explain this specific pulsar / SNR association. Even though $\tau_c > t_p$ for many other pulsars in SNRs, these results are still consistent with $\tilde{n} < 3$ (Kaspi et al. 2001b; Migliazzo et al. 2002). Gradual magnetic field growth may thus be widespread, but is only noticeable in a system such as the Duck for which its comparatively large age has allowed this effect to accumulate.

It is important to acknowledge that the large implied age ($t_p > 69$ kyr) is beyond what is expected for the observable lifetime of a SNR, which is typically $\sim 20 - 60$ kyr (Braun et al. 1989; Frail et al. 1994a). Thus even if magnetic field growth can explain the discrepancy between the pulsar's characteristic age and that inferred from proper motion, the large implied age is also a potential issue for SNR G5.4–1.2. However, the faint eastern rim of the SNR is consistent with what is seen for older, undisturbed shells, and may not have been easily identified on its own if not for the brighter western side. Thus the large age required for the SNR is not inconsistent with the appearance of this half of the SNR.

Furthermore, if the pulsar and SNR are physically associated, the discrepancy between the system's inferred age and the expected lifetime for observable SNRs can be resolved by the argument that the pulsar is re-energizing the SNR as it passes through it (Shull et al. 1989). The re-energization hypothesis predicts that brighter emission with a flatter spectrum should be seen along the western edge of SNR, and that these effects should peak where the pulsar would have crossed the rim. Indeed these phenomena are both observed (Fig. 1; Becker & Helfand 1985; Frail et al. 1994b). However, a requirement of this theory is that synchrotron-emitting particles must diffuse sufficiently rapidly away from the pulsar around the rim of the shell to produce the observed region of apparent interaction (van der Swaluw et al. 2002). We can quantify this as follows. If T is the time elapsed since the pulsar first began to interact with the SNR shell and X is the distance which is traveled by particles along the shell's circumference after injection by the pulsar wind, then we require $X = (2\kappa_{\mathrm{Duck}}T)^{1/2}$, where κ_{Duck} is the diffusion coefficient of synchrotron emitting particles as they move from the pulsar around the rim. From Figure 1 we estimate $X \approx 10$ pc and $T \sim 0.1 t_p \gtrsim 7$ kyr. We thus require $\kappa_{\mathrm{Duck}} \sim 2 \times 10^{27}$ cm^2 s^{-1} to explain the SNR's appearance.

We can determine if this inferred diffusion coefficient is reasonable by considering the magnetic field configuration through which particles must propagate. If the SNR is in the radiative phase as argued by GF00, then we expect strong compression at the SNR shock, and hence a magnetic field which runs parallel to the shell. Indeed radio polarization measurements clearly demonstrate this geometry to be present along the SNR's western rim (Milne et al. 1992). The mean free path in directions parallel to the magnetic field lines is larger than the electron gyroradius by a factor $\eta_{\mathrm{Duck}} = (\delta B_0/B_0)^{-2}$, where B_0 is the ambient magnetic field strength in the SNR shell and δB_0 is the amplitude of turbulent fluctuations in B_0 (Jokipii 1987; Achterberg et al. 1994). We can thus write $\kappa_{\mathrm{Duck}} = \eta_{\mathrm{Duck}}\kappa_B$, where κ_B is the standard Bohm diffusion coefficient, with value $\kappa_B \approx 1 \times 10^{23}(B_0/\mu\mathrm{G})^{-3/2}$ cm^2 s^{-1} for the 327-MHz image shown in Figure 1 (van der Swaluw et al. 2002). We then require $\eta_{\mathrm{Duck}} \sim 2(B_0/\mu\mathrm{G})^{3/2} \times 10^4$. In comparison, Achterberg et al. (1994) find $\eta_{\mathrm{young}} \lesssim 2000$ for young SNRs which have enhanced turbulence, but $\eta_{\mathrm{ISM}} \gtrsim 10^5$ for the ISM. If we assume a field strength $B_0 \sim 5 - 10$ μG, we thus find $\eta_{\mathrm{Duck}} \sim \eta_{\mathrm{ISM}}$, consistent with SNR G5.4–1.2 being an old remnant with reduced turbulent amplitude which is merging into the ISM (see also Moffett & Reynolds 1994). We conclude that the re-energization hypothesis is consistent with the expected rapid diffusion of particles from the pulsar around the shell rim.

As a final note, we point out that even if the pulsar is old, a small offset between the supernova explosion site and the SNR's geometric center is still required. Specifically, the trajectory of the pulsar as inferred from the cometary tail of the PWN passes north of the SNR's geometric center, indicating that the blast and geometric centers do not coincide (Fig.1; Frail et al. 1994b). Frail et al. (1994b) proposed that a gradient in the density of the ambient interstellar medium (ISM) into which the SNR is expanding could produce an asymmetric expansion, indeed resulting in a small offset between the explosion site and the SNR's center. Alternatively, Gvaramadze (2004) has proposed that the misalignment between the pulsar's expected and inferred trajectories could be due to a progenitor star which explodes slightly offset from the center of its wind-blown bubble (as already discussed in §3.1, but for the case of a young pulsar with a subtantial offset from the bubble's center). This again leads to the conclusion that the pulsar's true age is considerably in excess of its characteristic age (see Gvaramadze 2004).

3.3. *Chance Alignment*

The alternative simple explanation proposed by TBG02 is that SNR G5.4–1.2 and PSR B1757–24 have no physical connection. Given the relatively high density on the sky of both pulsars and SNRs in the inner Galactic plane, it is reasonable that two such objects could appear near each other in projection (Gaensler & Johnston 1995). H I absorption is only able to provide lower limits on the distances to the SNR and PWN (Frail et al. 1994b), while the pulsar's distance estimate as derived from its dispersion measure is model dependent and comes with significant associated uncertainties (see discussion by Cordes & Lazio 2002). Thus, although the distances to the two objects are consistent, TBG02 point out that this is not necessarily strong evidence in favor of an association.

Previous discussions had focused on the flatter spectrum and brighter emission of the SNR as evidence for an association, as described above. However, TBG02 point out that

variations in spectral index and asymmetries in brightness are both common in SNRs. In particular, many SNRs are brighter on the side closest to the Galactic Plane, as observed here. While these are valid arguments, we note that in most other SNRs in which spectral index variations are observed, these changes are spread randomly over the SNR, rather than concentrated in a particular region (Anderson & Rudnick 1993). More specifically, the systematic trend toward flatter spectra as one gets closer to the pulsar position around the rim of G5.4–1.2 is difficult to explain if the SNR and pulsar are unassociated.

3.4. *The Nature of G5.27–0.90*

An important additional aspect of this discussion is the nature of G5.27–0.90. As TBG02 note, the very tight angular coincidence of PSR B1757–24 and G5.27–0.90, along with the cometary morphology of the latter, make it virtually certain that at least these two objects are associated.

It is important to bear in mind that Figure 2 shows only the westernmost extent of this source. The inset to Figure 1 demonstrates that eastward of the pulsar, this structure broadens into a larger nebula, approximately $100'' \times 100''$ in extent. TBG02 interpret this overall morphology as a "Crab-like" PWN. In their model, the pulsar was born at the center of this larger nebula, and is now moving away from this site. However, there are difficulties with this interpretation. For the pulsar to have escaped from its own wind-driven bubble, the expansion speed of the PWN must have fallen well below the pulsar's space velocity. This process can only occur in two scenarios.

The first possibility is that as a PWN expands into the freely expanding ejecta of its associated SNR, it will eventually collide with the SNR reverse shock (Reynolds & Chevalier 1984; van der Swaluw et al. 2001; Blondin et al. 2001). The resulting interaction can reduce and even reverse the expansion of the PWN. Combined with the pulsar's ballistic motion, this compression of the PWN produces a morphology in which the pulsar is at the tip of a trail of radio/X-ray emission, connected to a larger "relic PWN". This scenario was invoked by van der Swaluw et al. (2004) to explain the morphologies of the PWNe seen in SNRs N157B and G327.7–1.1. The difficulty with this interpretation here is that to have produced a reverse shock, the SNR needs to have interacted with and swept up a significant amount of interstellar gas. The fact that we do not see any radio emission from an associated SNR makes this interpretation problematic.

The alternative possibility is that no significant outer blast wave was produced, as may be the case for the Crab Nebula and for 3C 58 (Slane et al. 2004; Seward et al. 2006). The PWN then interacts directly with the ISM, and has decelerated sufficiently as it sweeps up ambient gas that the pulsar is now able to overtake it. In this case we can write (Castor et al. 1975):

$$R_{PWN} \approx \left(\dot{E}/\rho \right)^{1/5} t^{3/5}, \tag{2}$$

where R_{PWN} is the radius of the "relic" component of the nebula at time t, ρ is the ambient mass density, and where we have assumed that the pulsar blows a steady wind of luminosity $\dot{E}$ into a uniform surrounding medium. For $t = \tau_c \approx 15$ kyr, $\dot{E} = 2.6 \times 10^{36}$ ergs s^{-1} and $R_{PWN} \approx 1$ pc, we then find an ambient number density $n_0 \sim 500$ cm^{-3}.

This high value can be ruled out by the morphology of the bow-shock component of the PWN. As discussed by GF00, the stand-off distance between the pulsar position and the

apex of the bow shock is $r_w \approx 0.04$ pc. This position is set by pressure balance between the pulsar wind and the ram pressure of the surroundings, $\dot{E}/4\pi r_w^2 c \approx \rho V^2$, where V is the pulsar space velocity. The left hand term yields a pressure $\sim 5 \times 10^{-10}$ ergs cm^{-3}. For the density inferred above, we then find $V \sim 10$ km s^{-1}. Not only is this velocity more than an order of magnitude slower than seen for young pulsars, but the solution is not self-consistent, since in 15 kyr, such a pulsar would only have traveled $\sim 0.1 - 0.2$ pc and so could not have moved outside its PWN bubble.

We thus conclude that there is no obvious explanation for G5.27–0.90 if PSR B1757–24 is ~ 15 kyr old and is unassociated with SNR G5.4–1.2.

On the other hand, if there is a genuine association between the pulsar and the SNR, then G5.27–0.90 could represent the remnants of the interaction between the pulsar wind and the SNR shell. van der Swaluw et al. (2003) consider the interaction between a high-velocity pulsar and a SNR in the Sedov-Taylor phase of evolution. They show that as the pulsar crosses the SNR, the drop in ram pressure from that in the SNR shell to that of the ambient ISM results in an expansion of the bow-shock structure. However, if G5.4–1.2 is in the pressure-driven "snowplow" phase of evolution (as argued by GF00 and as would be typical for the age inferred in Table 1), then the compression ratio of gas swept up by the forward shock will be much larger than the standard factor of four seen in the Sedov solution (e.g., Blondin et al. 1998). Therefore, during the period in which the pulsar breaks through the rim of the shell, the ram pressure experienced by the bow shock drops dramatically, which in turn should produce a sudden, explosive expansion of the pulsar wind nebula. As the pulsar moves outward, the pulsar wind blows a "Crab-like" structure into the ISM, which might possibly correspond to G5.27–0.90. Eventually the pulsar readjusts to its new, lower density environment, again forming a standard Mach cone, but connected to the larger relic structure left behind. This idea needs testing by full hydrodynamic modeling, but it provides a feasible explanation for the overall morphology of G5.27–0.90 in the scenario in which the pulsar is old and is associated with the SNR.

We note that Gvaramadze (2004) has proposed an alternate explanation for G5.27–0.90, in which this source is a slowly expanding lobe produced by the collimated flow of hot gas which follows the pulsar as it punctures the SNR shell. This similarly requires a physical association between the pulsar and the SNR.

4. CONCLUSIONS

The upper limit on proper motion we find for the PWN G5.27–0.90 is the most restrictive one obtained to date for this system. We are able to reject the original expectation that PSR B1757–24 was born ~ 15 kyr ago and is associated with SNR G5.4–1.2, regardless of whether the corresponding supernova occurred at the geometric center of the SNR, or at a site substantially offset from this.

Two possibilities remain. First, the pulsar and SNR are associated and share an age $\gtrsim 70$ kyr. In this case, the pulsar has a typical projected space velocity of $\lesssim 330$ km s^{-1}, which allows it to overtake its SNR at this stage and drive a bow shock through ambient gas. The sudden drop in pressure as the pulsar crosses the SNR's radiative shell might also explain the bulbous component of the PWN G5.27–0.90 seen between the pulsar and the SNR. The pulsar's passage has re-energized the radio emission from the SNR through rapid diffusion of pul-

sar wind particles along magnetic field lines; without this new injection of particles, the SNR would be much dimmer, would have a steeper spectrum and generally would be more difficult to detect. The slight offset between the pulsar's inferred trajectory and the SNR's geometric center possibly results from a density gradient into which the SNR is expanding, or from a slightly offset explosion within a pre-existing cavity. The only difficulty with this picture is that the system's age must then be many times larger than the pulsar's characteristic age, which is not seen in other pulsar / SNR associations. The proposed explanation is that the surface magnetic field of the pulsar is at the present epoch growing on a time scale of ~ 15 kyr. This effect is consistent with the properties of other pulsar / SNR associations, and is possibly also being seen in the long-term timing signatures of several pulsars (Lyne et al. 1996; Lyne 2004).

The alternative is that the pulsar is ~ 15 kyr old as indicated by its characteristic age, and is unassociated with SNR G5.4–1.2. This explanation eliminates the need to invoke off-center cavity explosions, re-energized shells or growing magnetic fields to explain the observations. However, this interpretation offers no easy explanation for the morphology of G5.27–0.90 which, contrary to the proposal of TBG02, cannot be easily explained as a relic nebula left behind at the pulsar's birth site. This model also requires that the brightened emission and flat spectrum of the SNR near the pulsar be a coincidence.

Frustratingly, a full understanding of the Duck remains elusive. However, future VLA or VLBA observations of PSR B1757–24 should eventually detect motion. Further-more, an X-ray detection of G5.4–1.2 and of the eastern parts of G5.27–0.90 should provide additional constraints on the properties of the system (see discussion by Kaspi et al. 2001a), while continued timing of the pulsar may be able to indicate the nature of the braking torque and magnetic field evolution in this source (e.g., Lyne et al. 1996).

Finally, other similar systems might provide additional clues. PSR B1951+32 is clearly in the process of puncturing the shell of the SNR CTB 80 (Hester & Kulkarni 1988; Fesen et al. 1988), while PSR J1016–5857 and SNR G284.3–1.8 have been proposed as another such interacting system (Camilo et al. 2001). Over the ensemble of Galactic pulsars and SNRs, Shull et al. (1989) predict approximately half a dozen systems in which the pulsar has recently penetrated the SNR shell. Searches for further interacting pairs may thus prove fruitful.

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TABLE 1
PROPER MOTION, VELOCITY AND AGE LIMITS ON G5.27–0.90 AND
B1757–24.

	GF00	TBG02	This paper
Proper motion (westward; mas yr^{-1})	< 24.8	< 37	< 13.9
Projected velocity (westward; km s^{-1})[a]	< 590	< 880	< 340
Age (kyr)[b]	$> 39 - 49$	$> 26 - 33$	$> 69 - 88$

NOTE. — All limits are given at 5-σ significance.

[a]Assumes a distance of 5 kpc to the pulsar and PWN.
[b]Assumes that the pulsar was born $\Theta = 16'.1 - 20'.6$ east of its current location, near the geometric center of SNR G5.4–1.2.

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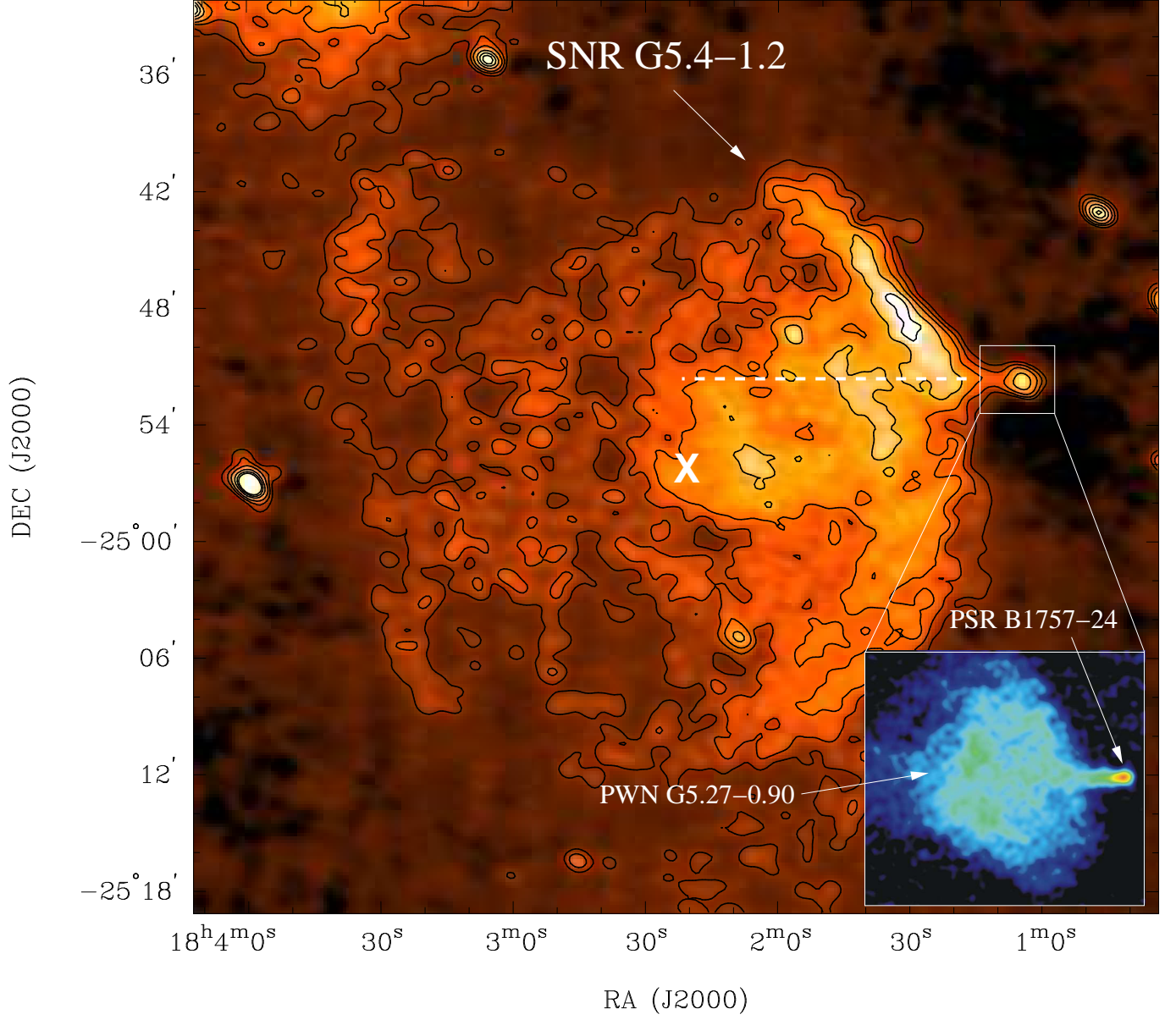van der Swaluw, E., Downes, T. P., & Keegan, R. 2004, A&A, 420, 937

FIG. 1.— VLA observations of "the Duck", with the SNR, PWN and pulsar indicated. The main panel shows a 327-MHz image of SNR G5.4–1.2 at a resolution of $55'' \times 41''$, adapted from GF00. Contours are at levels of 10, 25, 50 and 100 mJy beam^{-1}, and the peak intensity is 150 mJy beam^{-1}. The cross shows the approximate location of the center of SNR G5.4–1.2, while the horizontal line indicates the inferred direction of motion for the pulsar as implied by the morphology of G5.27–0.90. The inset shows a 8.5-GHz image of PWN G5.27–0.90, covering a $3'.5 \times 3'.5$ field at a resolution of $\sim 1''$ (image courtesy of NRAO/AUI and Dale A. Frail).
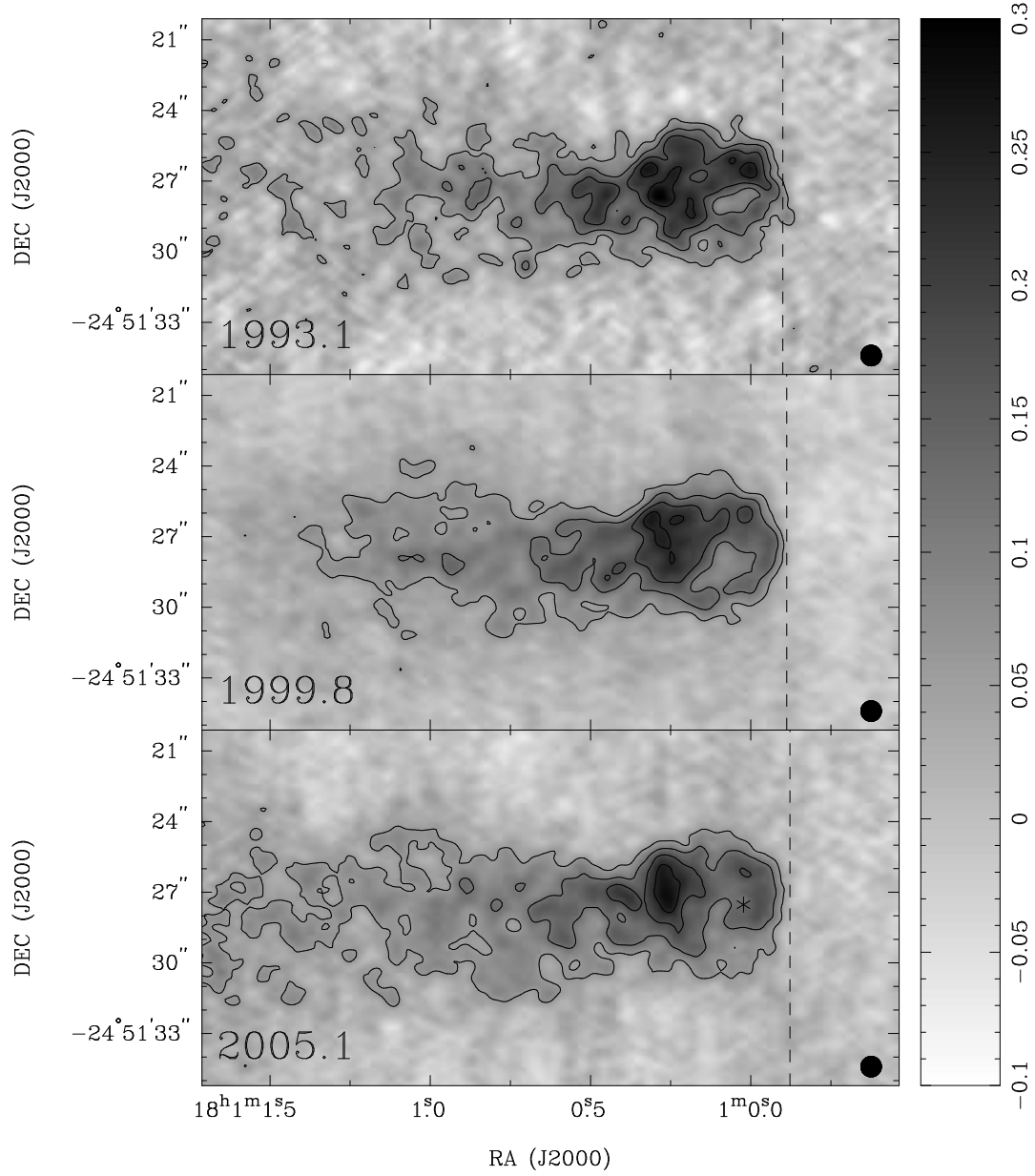
FIG. 2.— 8.5 GHz VLA observations of the western tip of PWN G5.27–0.90 at three epochs spread over 12 years. In each panel, the greyscale ranges from –0.1 to +0.3 mJy beam^{-1} (as shown in the wedge at right), while the contours are at levels of 0.6, 1.2, 1.8 and 2.4 mJy beam^{-1}. Each image has been smoothed to a resolution of FWHM 0″85, as shown by the circle at the bottom right of each panel. The position of PSR B1757–24 at epoch 2002.2, as given by TBG02, is marked by an asterisk in the bottom panel, and has an uncertainty much smaller than the size of the symbol. The vertical dashed line shows the expected relative shift for westward proper motion of 24.8 mas yr^{-1} (corresponding to the 5-σ upper limit previously determined by GF00). Note that the first epoch has poorer sensitivity than the second and third observations.